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PRESSURIZED FLUIDIZED-BED COMBUSTION A STATUS REPORT

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ABSTRACT

The first ever pressurized fluidized-bed combustor (PFBC) came into operation at the laboratories of the British Coal Utilization Research Laboratory at Leatherhead in 1969. This operated at pressures up to 6 atmospheres and ultimately had a thermal input of 4.5 MW. In the ensuing years, six other laboratory-scale combustors with thermal inputs ranging from 0.4 MW to about 2.4 MW and with working pressures up to 20 atmospheres came into operation. Scale up of the technology began in 1980.

Comprehensive data on combustion, hot gas cleanup and environmental aspects of the technology have been accumulated and design studies have shown that combined-cycle power plant based on PFBC have the potential to provide electric power at lower busbar costs than competing advanced power generating technologies.

This paper provides an overview on the development of the technology, the technical advances made, and those in the pipeline aimed at making the system even more attractive.

Introduction

Fluidized-bed combustion has the potential for (1) burning a wide range of fuels with minimal sensitivity to changes in fuel characteristics; (2) reducing the emission of sulfur and nitrogen oxides at low capital cost and with low thermal penalties; and (3) reducing the size and capital cost of steam-generating or air-heating equipment by virtue of (a) the higher rates of heat transfer achieved with tubes immersed in fluidized beds and (b) elimination of the need for large furnaces in which to cool molten ash particles by radiation before they enter the convection passes. The motivation to develop pressurized fluidized-bed combustion (PFBC) was to add to the foregoing the potential advantages of (1) more compact plant capable of a greater degree of shop fabrication (thus reducing capital cost) and (2) higher power generating efficiency by burning coal directly in combined gas and steam turbine power generating plant.

History

The potential benefits of PFBC were first actively pursued by the late Douglas Elliott while at the United Kingdom. Central Electricity Generating Board (CEGB) and his colleague, Raymond Hoy, at the then British Coal Utilization Research Laboratory (CURL) in late 1967. Their investigations centered on the possibility of enclosing a fluidized-bed system in a shell pressurized to several atmospheres. The objective of this approach was to utilize the hot pressurized combustion gases to turn the blades of a gas turbine in this case making the turbine coal fired to generate electricity. In 1969, they constructed the first-ever pressurized fluidized-bed combustor at Leatherhead, England. Work on PFBC at Leatherhead has, since 1972, mainly been funded by the United States Department of Energy Morgantown Energy Technology Center and its predecessors, and by organizations either directly or indirectly associated with it.

PFBC Configurations

PFBC, like so many other technologies, has a number of configurations; each has its own advantages and disadvantages. Typically, there are four basic configurations: steam cooled, air cooled, turbocharged boiler, and adiabatic.

- Steam Cooled -- Figure 1. The key aspects of this cycle are heat is extracted by boiling water; electricity is generated by combined cycles with approximately 75 percent from the steam turbine and 25 percent from the gas turbine; efficiency of the system is approximately 40 percent compared to a pulverized coal (PC) boiler (PC efficiency 35 percent); cost of electricity (COE) is approximately 9 percent less than a PC system; and capital costs on the average are 13 percent less than PC systems.

- Air Cooled -- Figure 2. The key aspects of this cycle are heat is extracted by air; stream is raised in a waste heat boiler; electricity is generated by combined cycle with approximately

60 percent produced from the gas turbine and 40 percent from the steam turbine in conjunction with the waste heat boiler; system efficiency is approximately 38 percent; dilution of flue gas stream with heated air from the in-bed tubes has the potential to provide longer gas turbine life. The primary disadvantage of air-cooled combined cycle is that the economics of the system are not competitive with either the PC systems or the steam-cooled combined cycle.

- Turbocharged -- Figure 3. This system will no doubt be the first entrant in the commercial market. The key aspects of this configuration are heat is extracted with steam; electricity is generated by single-cycle steam turbine; gas turbine expands flue gas to pressurized air only; exit gas from the PFBC boiler is appreciably lower (825°F). Low exit temperature is felt and will reduce the concern of corrosion in the downstream gas turbine; however, erosion is still a concern. The overall economics of the turbocharged boilers are slightly improved over PC systems, COE and capital costs are reduced by 2 to 4 percent, and system efficiency is improved by 3 percent.

- Adiabatic -- Figure 4. This system avoids the in-bed tube erosion problem that exists in FBC systems by eliminating the in-bed tubes. The electricity is generated by combined cycle with approximately 40 percent from the steam turbine and 60 percent from the gas turbine. Steam is raised in the waste-heat boiler. The general efficiency and costs are similar to the air-cooled systems. The gas turbine is totally reliant, however, on the gas cleanup system as there is no opportunity for dilution of the flue gas.

As one would expect, based on this brief overview of the configurations, the configuration of preference is the steam-cooled combined cycle. Figure 5 summarizes the overall plant efficiency versus turbine inlet temperature. It is rather obvious that as one goes up in temperature, the overall system efficiency also increases. Steam-cooled systems have the better performance curve.

PFBC Operating Parameter Studied

The ranges of conditions explored in the principal test rigs, noted in Table 1, include the following: (1) Thermal inputs from 0.2 to 60 MW, operating pressures from 5 to 20 atmospheres and bed plan cross-sections from 1.17 m^2 to 11 m^2. (2) Bituminous coals with normal volatile matter contents (a few with low volatile content) and subbituminous coals and lignites have been burned with ash contents ranging from 7 to 44 percent. (3) Both limestone (raw and pre-calcined) and dolomite have been used as SO_2 sorbents. Sorbent has normally been fed dry but has also been fed as a slurry. (4) Fluidizing velocities as high as 3.0 m/s have been used over long test periods although the majority of the test work has been at 0.8 m/s or below. (5) Bed temperatures have been in the range of 700° to 950°C. (6) A predominance of the testing has been carried out at excess air values about or above 30 percent. (7) Coal has mainly been fed dry (approximately zero surface moisture), crushed to the size appropriate to the fluidizing velocity, and transported to the bed in air after pressurization in lockhoppers. (8) Coal-water slurries, both with a top size of about 300 microns and 3 mm, have been used. (9) Both tapered and parallel bed combustor geometries have been tested. (10) The fouling, erosion, and corrosion propensities of the combustion gases after cleaning in cyclone type dust collectors have been assessed by passing them through cascades of turbine blades/airfoils or small rotating blade assemblies having the characteristics shown in Table 2.

Process Data Results

- Combustion Efficiency -- Efficiencies close to or about 99 percent can be expected where the bed temperature is about 850°C, excess air is above 30 percent, gas residence time in the bed is 3 seconds or longer, and the coal being burned ranges from medium to high volatility.

  Combustion efficiency appears to be slightly less dependent on bed temperature when the coal is fed as a coal-water slurry. The slurry tends to form globules of carbonaceous material as it leaves the nozzle. These probably incorporate the fines in such a way to increase their residence time in the bed.

  Scaling up from the small rigs to the larger pressurized fluidized-bed combustors ($4m^2$) has not so far resulted in significant deviations from the combustion efficiency predictions based on existing correlations.

- Sulfur Capture -- The ability to meet emission regulations at an acceptable cost for SO_2 sorbent is of paramount importance to the success of PFBC. Reliable predictions of sulfur capture by limestone or dolomite added to the bed still relies heavily upon carrying out test work under operating conditions closely approximately to those that will apply in commercial plant.

  Performance is influenced by many factors and interactions: notably, residence time in the bed and freeboard, bed temperature, reactivity of the sorbent (particularly accessibility of the pore structure), particle size, and oxygen concentrations at the bottom of the bed. Correlations have been evolved that take these into account reasonably well and from which the sulfur capture performance in a large combustor can be predicted with a reasonable degree of confidence using the results of tests carried out in a small combustor.

  On the basis of calcium/sulfur ratio, dolomite is about twice as effective as limestone, and 90 percent sulfur capture can be expected with dolomite with a Ca/S mole ratio of 1.5 under typical PFBC operating conditions.

  The most promising approach to achieve consistently high sulfur capture appears to be (a) to use low fluidizing velocity; this results in a smaller bed particle size (b) to use deep beds and hence long residence times, and (c) to recycle fines captured by the primary gas cleanup stage.

  Sulfur capture may also be improved by as much as 30 percent by adopting two-stage combustion (Reference 13). The engineering problems involved in supplying air at two levels in a large bed are, however, formidable, and from this point of view, it is probable that alternative solutions will be explored first.

- NO_x Emission -- NO_x emissions from PFBC's operated under conditions of commercial interest are generally well within current regulatory requirements.

Since there are already more stringent requirements in some locations, and there is a possibility of these becoming more widespread, tests have been made utilizing two-stage air admission. Experiments to date (Reference 13) with two-stage air admission have shown marginal improvements that would not justify the cost and complication involved in overcoming the considerable engineering problems involved in providing an additional air distributor.

- Elutriation -- Gas borne material leaving the bed includes particles of elutriable size from the coal and sorbent feeds, breakdown products from both, incompletely reacted coal particles, and material "splashed" out of the bed due to eruption of bubbles. The extent to which the latter enter the hot gas cleaning system depends upon factors such as freeboard height and gas velocity.

  Significantly more material has been elutriated from large (4 m^2) than from small combustors (0.54 m^2) operated under otherwise similar conditions. The large cross-sections most probably allow full growth of bubble size and energy, and hence, "splash" effects are increased, and there also appears to be greater breakdown of sorbent particles in the larger beds. The net effect appears to be about double the amount of material elutriated compared with "small" bed operation.

  It is thought that loss of material by splashing could be significantly reduced by having much more closely spaced tubing at the top of the tube bank than in the remainder.

- Alkali Emissions -- Alkali particularly in association with sulfur compounds are the principal sources of corrodents at high temperature. Alkali enter the PFBC system in the coal ash and in the sorbent. They leave the system primarily via the excess material discharged from the bed and in the dust discharged from the cyclones. About 5 percent will typically be present in the combustion gases and dust particles. This concentration is much in excess of what is deemed to be acceptable in oil-fired gas turbines, but the presence of fine particulate matter together with the lower temperatures and the corrosion resistant materials envisaged for the coal-fired plant can be expected to provide some compensation.

  The indications have been that lower exit gas temperatures and proper materials/coatings may provide satisfactorily long blade life. Further, by limiting operating temperature, it has also been shown that dust deposited on blades can be readily removed using conventional on-line cleaning methods.

Engineering Developments

Reliability will be a major factor in the adoption of PFBC systems. The beneficial effects of higher power generating efficiency and lower capital cost are rapidly lost if the availability of the plant does not match that of current systems. The status of development of the various components of a PFBC system can be summarized as follows:

- Solids Preparation, Pressurization, and Feeding -- Experience has confirmed the need to remove surface moisture to ensure reliable feeding of solids in pneumatic systems. The lockhopper, despite the high-energy loss incurred and the requirement of inert gas for pressurizing, is currently the only proven means for introducing dry coal into a pressurized system. Rotary valves are now available for controlling the rate of feed from pressurized hoppers into pneumatic transport systems, though they have been subject to failure due to the erosive environment in which they operate. These can provide much more satisfactory control of flow than any solely pneumatic system and involve lower feeder hopper pressures.

  Investigations with small rigs have shown that stable coal-water mixtures containing 70 percent of coal with a top size of 3 mm can be produced without the aid of additives, and that these can be reliably pumped into combustors operating at high pressures (e.g., 16 atmospheres). The sorbent can also be incorporated into a coal-water mixture albeit with an increase in the water input to the combustor. The indications are that commercially available preparation and pumping equipment should be adequate to reliably and economically meet the requirements of large PFBC plant. There is hope for developments to (1) enable run-of-mine coal to be used without the need for preparation other than to reduce the top size to about 25 mm and (2) evolve an alternative to the lockhopper for pressurizing that will have lower energy losses and obviate the need for using inert gas for pressurizing the contents.

- Combustor Design -- The future trends are seen to be: (1) to operate at relatively low fluidizing velocity (e.g., 1 m/s) and with deep beds (e.g., 3 m upwards) to enhance combustion and sulfur capture performance; (2) to use combustors with tapered beds in order to simplify air distributor design and distribution of the coal and the removal of excess material from the bed; and (3) to use change of bed level as well as bed temperatures as the means for changing load.

  Areas where the differences of approach are most apparent are in distribution of heat transfer surface and in the design of the combustor containment. The main alternative as regards heat transfer surface are whether or not the functions of evaporation, superheating, and reheating are carried out in separate beds each with separate control on firing rate or whether they are confined into single beds. The principal contenders as regards combustor containment are the large sphere designed to contain both the combustor and the bulk of the hot gas cleaning equipment or separate cylindrical vessels for the combustor and the gas cleaning system.

  Needed developments include the (1) evolution of tube bank geometries and means of protecting tubes that will result in tolerable rates of metal wastage when fluidizing velocities higher than 1 m/s are used; (2) ability to use run-of-mine coal without accumulation (e.g., rocks, etc.) particles in the bed that can lead to defluidization; and (3) means to enable more rapid heating up of the bed and thereby shorten start-up time particularly for two-shift operators.

- Load Control -- Control of load in a system involving steam and gas turbine plants and a combustion system with significant inertia is inevitably complicated. This has received attention in the test work. The data obtained on system response to changes in firing rate have contributed to the formulation of designs for control systems over which there is now increased confidence.

- Hot-Gas Cleanup -- Cyclones appear to be capable, when operating as intended, of removing particles from the gas stream that are larger than 10 microns. It is conceivable that three stages of cyclones might be sufficient to reduce the dust loading acceptable to a large industrial gas turbine where relative velocities are low. It is most unlikely, however, that the dust loading will approach that needed to meet the U.S. EPA emission limitation of approximately 22 ppm, and hence, the turbine would need to be followed by an electrostatic precipitator or a baghouse filter.

  The elimination of the need for this large and expensive equipment by the development of particulate removal equipment suitable for installation ahead of the turbine is an important objective.

- Solids Removal and Depressurizing -- The principal means for depressurizing dust/ash is the lock-hopper. Developments in recent years have led to valves that will seal in hot and dusty environments. The valves are expensive and maintenance requirements can be severe; consequently, the approach now being adopted is to cool the solids before they enter the lock hopper system. There is considerable scope for refinement if capital and operating costs are to be minimized.

Summary

A technology cannot be said to have achieved its promise until a large plant has been operated sufficiently long to demonstrate reliable attainment of the target level of performance and the potential that the plant can be built commercially for a cost that is significantly below that of a conventional plant.

The technology has, however, progressed from the laboratory scale to a scale of operation from which reasonably confident extrapolations can, in most respects, be made to operate on the large plant scale.

The status of the development from the engineering point of view appears to be that the combustor and cleanup systems may provide satisfactory operation on the large plant scale. Other issues in terms of fuel feeding, erosion, corrosion will require significant advances and refinement in order to achieve the projected capital/operating costs savings and reliability/availability needs of the utility sector. The authors think that the prospects for success are good but significant work remains to solve key technological issues. The current increase in interest in application of the technology on the part of the power industry is encouraging.

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STEAM-COOLED PFB COMBINED CYCLE

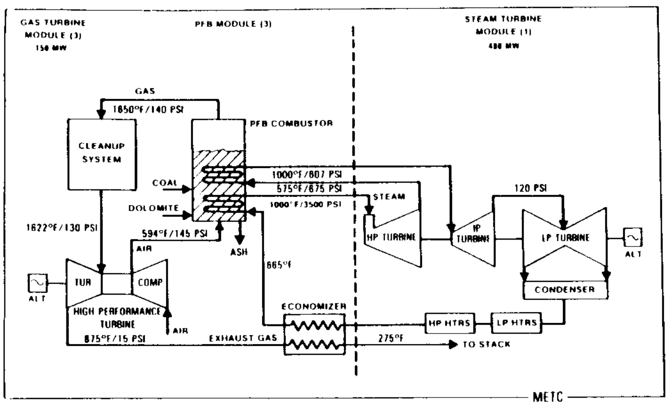

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Figure 1

AIR-COOLED PFB COMBINED CYCLE

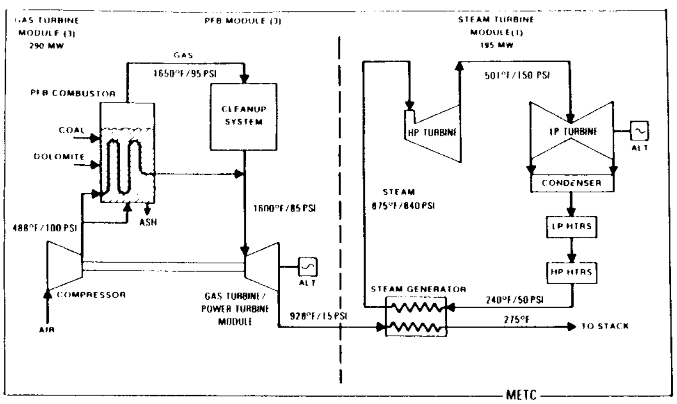

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Figure 2

Turbocharged PFB Simple Cycle

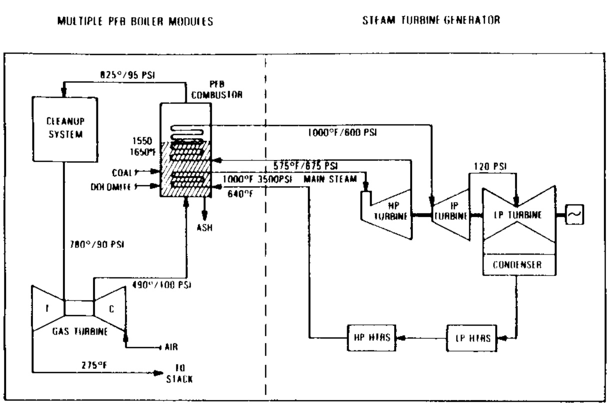

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Figure 3

Adiabatic PFB Combined Cycle

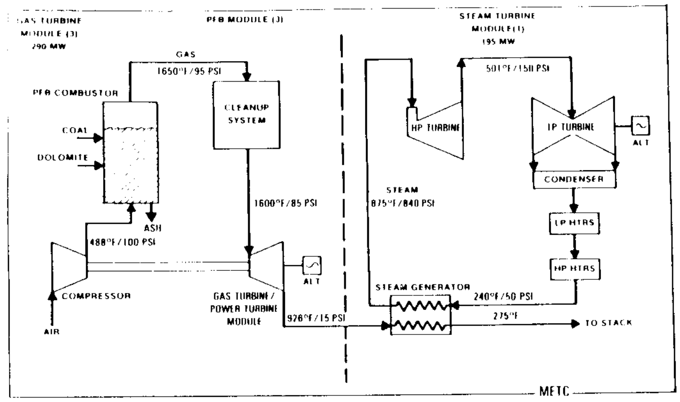

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Figure 4

Plant Efficiency Versus Turbine Inlet Temperature

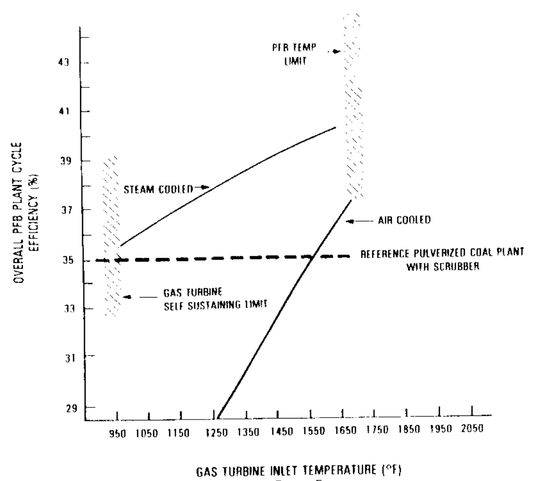

Figure 5

TABLE 1

PFBC Test Rigs 150 mm or Larger

Name	Maximum Rating MW	Bed Plan Area m^2	Depth (Maximum) m	Temperature (Maximum) C°	Fluidizing Velocity m/s	Maximum Pressure Atm	Status
Argonne National Laboratory U.S.A.	0.15	0.02	0.9	980	1.8	6	Operational
NASA Lewis Laboratory U.S.A.	0.5	0.04	2.4	870	2.1	8	Not In Use
Exxon Eng. U.S.A.	1.7	0.07	< 3.6	980	2.1	10	Not In Use
New York University U.S.A.	7.0	0.46	3.6	950	2.4	10	Operational
General Electric Malta, U.S.A.	3.6	0.07	1.6	950	0.9	10	Operational
Curtiss-Wright SGT (Airheater) U.S.A.	4.9	0.66	4.9	900	0.8	7	Not In Use
Curtiss-Wright Pilot Plant U.S.A.	39.0	13.06	4.9	900	0.8	7	Not Commissioned
NCB CURL 1 U.K.	6.0	0.6-0.80	2.8	950	2.1	6	Not In Use
NCB CURL 2 U.K.	0.3	0.7	1.2	950	3.7	6	Not In Use
NCB CURL 3 U.K.	2.0	0.10	3.1	950	1.5	20	Operational
IEA Grimethorpe U.K.	60.0	4.00	4.5	950	2.5	12	Operational
ASEA PFBC Sweden	15.0	2.00	app. 3.7	900	0.9	16	Operational

TABLE 2

Equipment for Assessing Erosion Characteristics of PFBC Gases

Rig	Type of Equipment	Mass Flow kg/s	Erosion Target	Maximum Gas Velocity m/s
Exxon 1000 h.	GE Type Airfoils 4 Rows of Six	app. 0.5	Bar	app. 400
CURL 1000 h.	Test 1 Similar to Exxon	app. 0.5	Bar	app. 400
	Test 2 Stal-Laval Turbine Blade Section	app. 0.9	Rod	app. 520
Grimethorpe	GE Type Airfoils 4 Rows of Nine	app. 5.5	Bars	app. 400
ASEA PFBC Malmo	Rotating Blade Assembly	To Follow	--	To Follow
Curtiss-Wright 1000 h.	Rover Gas Turbine Rotor	app. 0.5	Blades	app. 415
GE/LTHT 5500 h.	Airfoils 4 Rows of Six	app. 0.2	Rods	app. 400